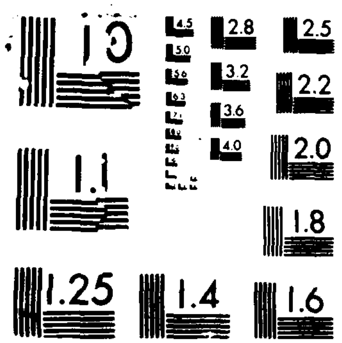

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USE OF BLADE SWEEP TO REDUCE 4/REV HUB LOADS

Darrell K. Young
Senior Engineer, Dynamics Projects

and

Frank J. Tarzanin
Supervisor, Dynamics Projects
Boeing Vertol Company
Philadelphia, Pennsylvania

Donald L. Kunz
Research Scientist
Aeroflightdynamics Directorate
U.S. Army Research and Technology Activity (AVSCOM)
Moffett Field, California

Abstract

The effect of blade planform sweep on the 4/rev hub loads for a four-bladed, fully-articulated rotor was analytically investigated. A previous study [1] showed that substantial vibratory hub load reductions could be achieved by using aft tip sweep. However, the mathematical model and the blade definition were too complex to understand the source of the reduction. To aid in understanding the physical mechanism, a model of a simplified blade was defined that still showed substantial hub load reductions. Using this simplified model, an extensive blade parameter sensitivity study was performed. It was determined that those properties which are related to the dynamic torsional response of the blade were important in determining the effectiveness of both aft and forward tip sweep in reducing the 4/rev vertical hub load. An extensive investigation into the source of the hub load reduction was performed, and a number of hypotheses were developed.

Introduction

Rotorcraft vibration is a subject that over the past few years has received increased attention from helicopter engineers. New and innovative methods of reducing vibrations have been developed through joint Government and industry participation in advanced research programs. One approach to reducing the vibration levels is to design the rotor to have low vibratory hub loads [1-9]. This approach provides a unique opportunity to minimize vibrations at the source.

In a study performed for the Aeroflightdynamics Directorate of the U. S. Army Research and Technology Activity (AVSCOM), the Boeing Vertol Company analytically investigated the possibilities and methods of reducing helicopter rotor hub vibratory loads through the use of blade tip sweep [1,2]. The importance of sweep initiation radius, sweep angle, and blade properties were investigated. Several hypotheses were also developed to identify the hub load reduction mechanism.

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Baseline rotor

The basic rotor used during this study was a four-bladed, fully-articulated rotor having a tapered planform (Figure 1), advanced airfoils, a radius of 24.85 feet and an operating nominal rotor speed of 269 rpm. The blade chord and pitch arm were 22 inches and 8.5 inches respectively. Table 1 contains a summary of the flight conditions used and Table 2 contains the nondimensional in vacuum blade natural frequencies.

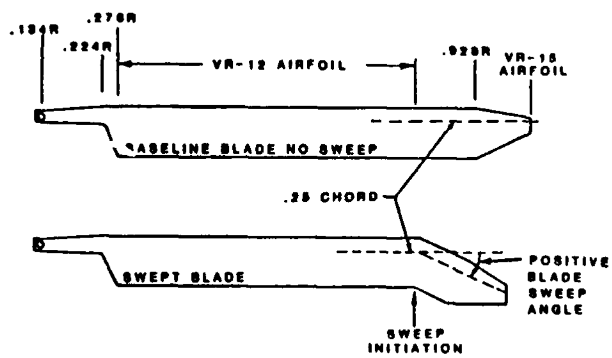

Figure 1. Blade geometry.

Table 1. Rotor flight conditions.

Airspeed = 150 knots
Sweep angle = 0 degrees
Rotor speed = 269 RPM
Air density = .002378 lb.-s^2/ft^4
Thrust = 16463 lb.
Thrust C_T/σ = .0775
Lateral cyclic = -2.9 degrees
Longitudinal cyclic = -7.0 degrees
Collective = 13.9 degrees
Advance ratio = .356
Propulsive force = 1396 lb.
Propulsive force C_x/σ = .00657

For airspeed sweeps, the propulsive force was scaled by the square of the airspeed. This minimized the parametric changes which could mask the effect of sweep at other air speeds.

Table 2. Summary of the in vacuum blade frequencies for the baseline rotor, simplified model blade and three of the blade models used in the sensitivity study for an unswept blade.

Mode	Baseline	Simplified model	1.5 x GJ inboard	.04 x chord CG shift	3 x mass .79-.83R
1st flap	1.02	1.02	1.02	1.02	1.02
2nd flap	2.53	2.62	2.62	2.61	2.92
3rd flap	5.67	4.72	4.72	4.72	4.85
4th flap	8.79	7.51	7.51	7.50	7.50
1st chord	.54	.55	.55	.55	.52
2nd chord	5.63	6.22	6.22	6.22	6.35
1st torsion	4.35	4.25	4.93	4.26	4.25

The Boeing Vertol aeroelastic rotor analysis program, C-60, was used during the investigation. This analysis is a complex, state-of-the-art, computer program that includes such features as elastic blades with nonuniform properties and full flap, lag, and pitch coupling, an inflow model with a discrete vortex wake and nonlinear, three-dimensional unsteady aerodynamics [10,11,12].

The primary hub load of interest for this study was the 4/rev vertical hub load. Figure 2 shows the effect of the sweep initiation radius and aft sweep angle (denoted as a positive sweep angle) on the 4/rev vertical hub load at 150 knots. Of the three initiation radii, .87R produces the most consistent reduction in the 4/rev vertical hub load through 30 degrees of aft tip sweep. Hence the remainder of the study used a sweep initiation radius of .87R.

Figure 3 shows the effect of sweep angle on the 4/rev vertical and effective inplane hub loads, the 4/rev effective hub moment, and the amplitude of the alternating pitch link load at several airspeeds. (The effective load refers to the square root of the sum of the squares of the amplitude of lateral and longitudial loads). While the largest reduction in hub loads occurs in the vertical direction for 30 degrees of sweep at 150 knots, the most consistent hub load reduction over the given airspeed range (100 to 220 knots) occurs for 20 degrees of sweep. Overall, the basic trend is that the 4/rev hub loads and rotor power can be reduced by the use of blade tip sweep.

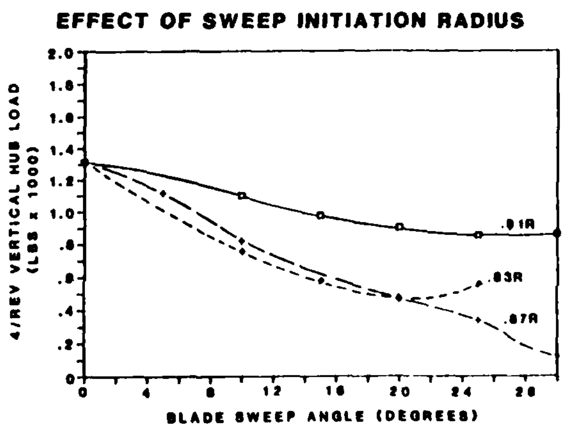

Figure 2. Effect of sweep initation radius and sweep angle on the 4/rev vertical hub load.

Table 3. Comparison of baseline rotor blade with a similar wind tunnel tested model blade.

Mode	Natural frequencies (per rev) Baseline Blade (Tapered Tip)	Model Blade (Square Tip)
2nd flap	2.53	2.54
3rd flap	5.67	5.10
4th flap	8.79	8.44
1st chord	.54	.49
2nd chord	5.63	5.99
1st torsion	4.35	4.90
Blade radius	24.85 ft.	5.0 ft.

Correlation of calculated 4/rev vertical hub loads with similar scaled model wind tunnel test data

The baseline rotor was a full scale definition of an earlier advanced rotor concept. To check the validity of the C-60 analysis, the 4/rev vertical hub load calculated for the baseline blade was compared with wind tunnel test results for a scaled model of a similar rotor blade.

EFFECT OF SWEEP ON BASELINE ROTOR

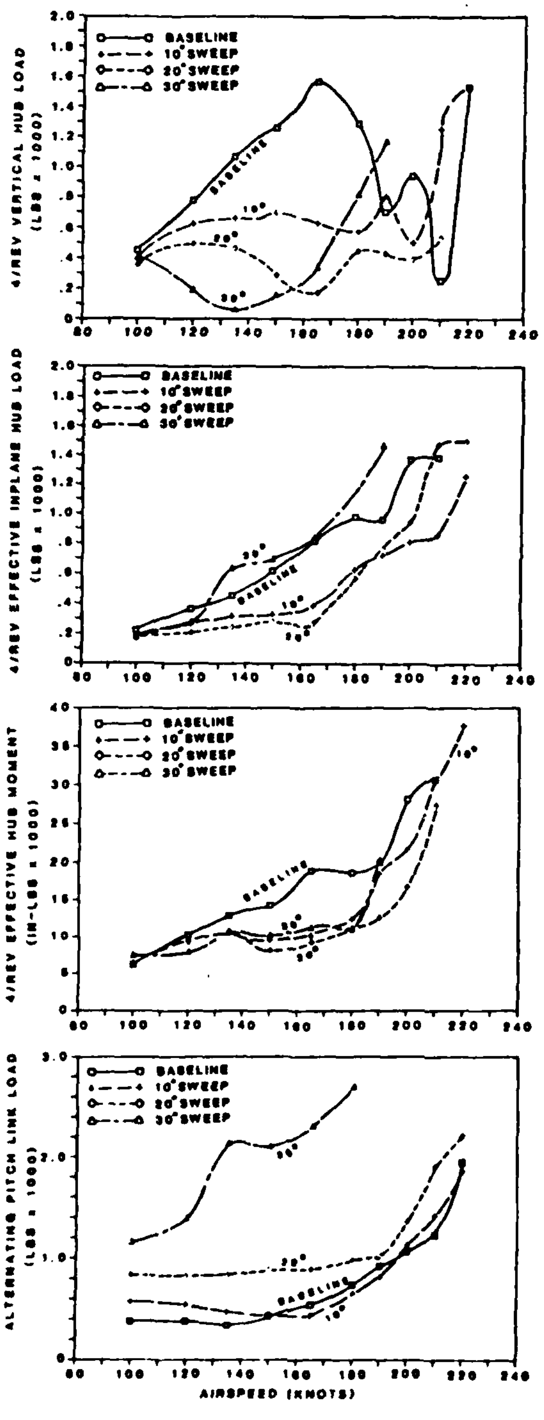

Figure 3. Effect of aft sweep and airspeed on the hub loads for the baseline rotor.

COMPARISON OF 4/REV VERTICAL HUB LOAD

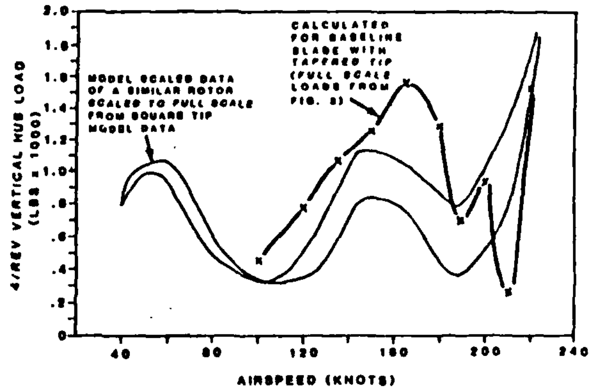

Figure 4. Comparison of 4/rev vertical hub loads calculated for a full scale rotor and scaled from similar model test data.

A square tip model having the same airfoils as the full scale *baseline rotor* was tested at Boeing Vertol in 1980. A comparison of the natural frequencies and blade radius for each blade is provided in Table 3. As shown in the table, the frequencies are similar and are close enough for gross comparisons.

Figure 4 compares the 4/rev vertical hub load calculated by C-60 with the experimentally measured data. The correlation is reasonable (considering the mass and stiffness distributions, and the rotor trim are different).

Simplified rotor blade model

The investigation performed up to this point utilized a rotor blade with a complex distribution of blade properties over the blade span, which prevented the authors from gaining a clear understanding of the physical phenomena responsible for the sweep-induced hub load reductions [1]. Thus, it was decided that a simplified analytical model that would show a similar 4/rev vertical hub load reduction trend should be defined.

The simplified blade model used constant spanwise properties, and a constant chord (i.e., square tip). In addition, the C-60 aeroelastic rotor analysis program was used with uniform downwash instead of nonuniform downwash. Table 2 contains the blade natural frequencies in a vacuum for the unswept simplified model blade. Comparing the simplified blade model with the baseline blade shows that the 3rd and 4th flap frequencies are reduced while the 2nd flap and 2nd chord frequencies are increased.

To ensure that the 4/rev hub load trends with airspeed were not drastically changed, an airspeed sweep was run using the simplified model. As shown in Figure 5, 10 degrees of aft tip sweep is clearly superior to no sweep up to 210 knots for the 4/rev vertical hub load. Also the 4/rev vertical hub loads for zero and 10 degrees of aft tip sweep show the same trend as the complex, nonlinear model (Figure 3). However, the simplified model experienced divergence problems. Notice that the simplified model could not fly past 220 knots, while the unswept baseline blade could. Also note that the 20 degree swept simplified model diverged before 160 knots, and the 30 degree swept simplified model diverged for all airspeeds between 120 and 240 knots.

The other loads for no sweep and 10 degrees of sweep (Figure 5) are similar to those for the baseline blade (Figure 3). The exceptions are the 4/rev effective inplane hub load and effective hub moment where, at some airspeeds, 10 degrees of aft tip sweep produces higher loads than the unswept blade.

It is clear that the simplified blade properties changed the sweep effectiveness in reducing the 4/rev hub loads. But the simplified model still demonstrated the essence of sweep-induced vibration reduction and made an appropriate starting point for a blade parameter sensitivity study.

Blade parameter sensitivity study results

The blade parameter sensitivity study was conducted at 150 knots using the simplified model discussed above. The values of each blade physical property were varied over different spanwise regions of the blade in order to determine their impact on the 4/rev vertical hub load. The blade physical properties were varied for three regions — across the whole blade, inboard of the sweep initiation radius, and outboard of the sweep initiation radius. Table 2 contains the blade natural frequencies in a vacuum for the three sensitivity models described below. Property changes that had less impact on the vibratory hub load reduction are discussed in more detail in Reference 2.

The stiffness property which influenced the 4/rev vertical hub load the most was the torsional stiffness, particularly when it was varied over the inboard portion of the blade. As shown in Figure 6, a stiffness factor of 1.5 (i.e., a stiffness value that is 1.5 times the simplified model value) produced the lowest vertical hub load at 25 degrees of aft tip sweep. By using 25 degrees of aft tip sweep instead of no sweep (for a stiffness factor of 1.5), there was an 89.3% reduction in the hub load. However, when the stiffness value was increased even more (e.g., 2x and 4x), the vertical hub load started to increase with increasing sweep angle. Hence, increasing the torsional stiffness too much destroys the ability of aft tip sweep to reduce the 4/rev vertical hub load.

EFFECT OF SWEEP ON SIMPLIFIED MODEL

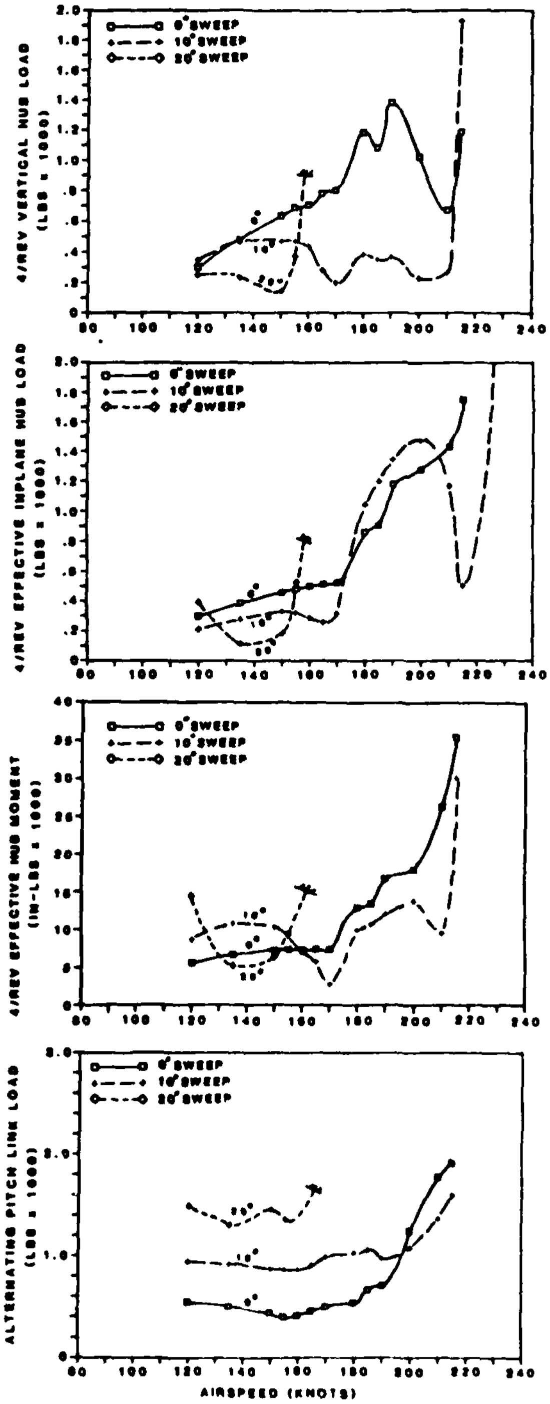

Figure 5. Effect of aft tip sweep and airspeed on the hub loads for the simplified model.

TORSIONAL STIFFNESS (GJ) SENSITIVITY (INBOARD) AT 150 KNOTS

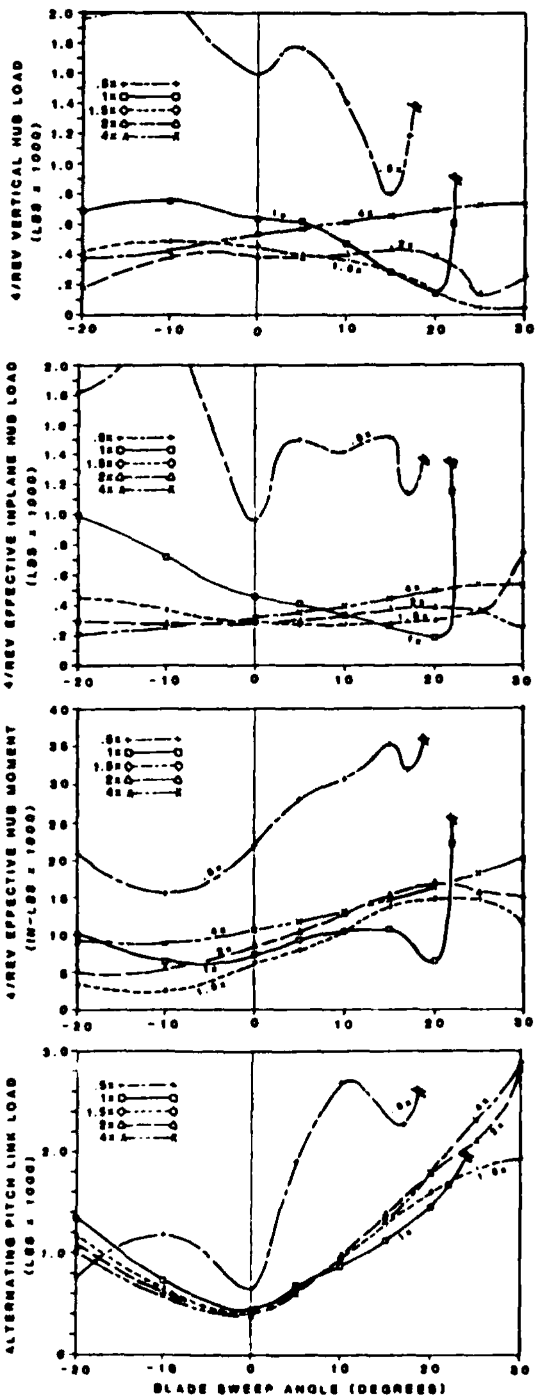

Figure 6. Effect of varying the torsional stiffness inboard of the sweep initation radius on the hub loads.

CHORDWISE CENTER OF GRAVITY SENSITIVITY (WHOLE BLADE) AT 150 KNOTS

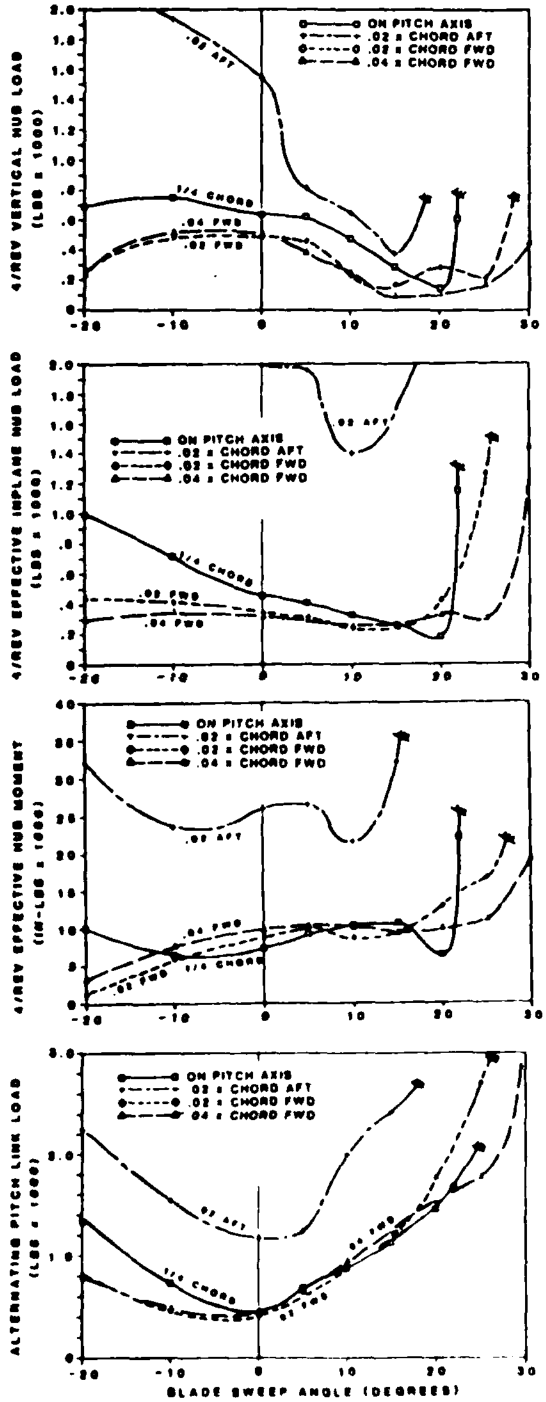

Figure 7. Effect of varying the chordwise center of gravity along the whole blade on the the hub loads.

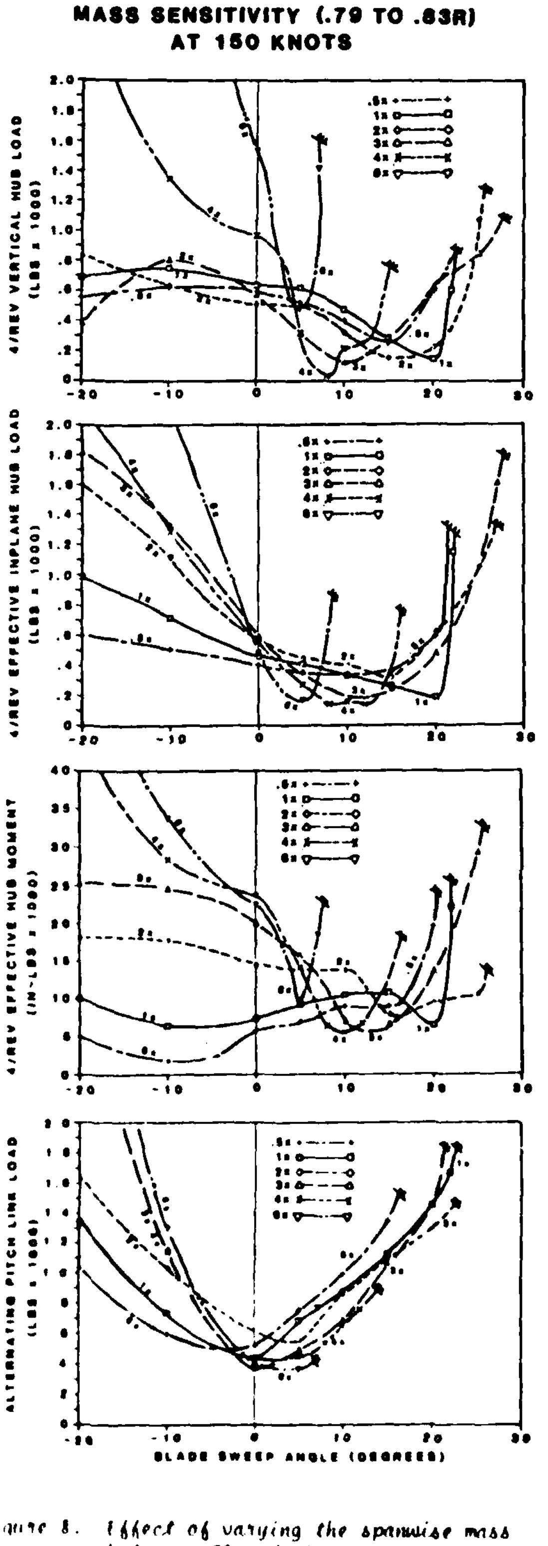

Figure 8. Effect of varying the spanwise mass between .79 and .83R on the hub loads.

Another property which improved the reduction of the 4/rev vertical hub load with aft tip sweep was the chordwise center of gravity location (Figure 7). By moving the center of gravity 4% (of chord) forward of the quarter chord along the whole blade, the 4/rev vertical hub load was reduced when 15 degrees of aft tip sweep was used instead of no sweep. (The center of gravity for the baseline blade and original simplified blade was at the quarter chord.)

When the value of the spanwise mass distribution between .79R and .83R (just inboard of the sweep initiation radius) was varied by a factor of three, the 4/rev vertical hub load showed the greatest reduction (Figure 8). This is a 77.6% reduction in the 4/rev vertical hub load which was achieved by using 10 degrees of aft tip sweep instead of no sweep. However, as with the torsional stiffness, there is a penalty to pay for having too much mass. As the mass factor increased (e.g., 4x and 6x), the bucket got narrower and the 4/rev vertical hub load for no sweep began to increase.

Hence, it appears that the torsional dynamic response of the blade determines the effectiveness of tip sweep. Other authors [3-9] have reached the same conclusion but have also experienced difficulties in understanding the sweep mechanism. Based on their comments and recommendations, several blade characteristics were plotted verses blade azimuth angle in an attempt to better understand the sweep mechanism.

Tip angle of attack

One of the tools used as a guide in trying to determine the sweep mechanism was the tip angle of attack. A previous study [1] showed that the tip angle of attack was reduced on the advancing side (Ψ = 90 degrees) by using aft tip sweep. Gupta [6] also points out that a nonzero, advancing-side, tip angle of attack produces higher vibrations when compared to the case when the advancing-side tip angle of attack is zero. However, when the tip angle of attack was plotted for several of the blade models used during the sensitivity study, the sweep angle at which the 4/rev vertical hub load was a minimum did not always correspond with the sweep angle which had the lowest advancing-side tip angle of attack.

This failure of the tip angle of attack to correlate with the vibratory hub load may be due to the very simple method used to evaluate the advancing-blade angle of attack. Using only one blade spanwise position (the blade tip) and only one blade azimuth position (90 degrees) may be far too simplistic. To check this premise further would require some procedure for obtaining an effective advancing-blade angle of attack over the whole blade for the advancing-blade region (azimuth angles 45 to 135 degrees).

Load reduction mechanism hypotheses

Our current understanding of the hub load reduction mechanism is that there is a cg-ac (chordwise center of gravity - aerodynamic center) offset effect occurring on the unswept portion of the blade when the tip section is swept either forward or aft. By a cg-ac effect, we mean that the aerodynamic forces acting at the blade local aerodynamic center and the dynamic inertial forces acting at the blade chordwise center of gravity produce a twisting moment on the unswept portion of the blade, thereby generating favorable elastic blade twist. This favorable elastic twist changes the blade angle of attack, altering the vibratory airloads, which results in a reduced 4/rev vertical blade root shear. However, we do not know the necessary and sufficient conditions for this 'favorable' elastic twist to occur, and we do not fully understand the mechanism that causes this elastic twist. Two effects have been identified that act on the blade due to tip sweep, and it is not known if they act together or independently. These effects are

- advancing blade untwist or twist reduction (quasi-static), and
- favorable higher-harmonic elastic pitch.

Advancing blade untwist

For the advancing blade in forward flight, the tangential velocity along the blade is much larger than it is in the hover condition, since the helicopter forward speed adds to the rotor rotational velocity. For this case, the axial-flow-induced angle of attack difference between the tip and root of the blade is smaller than the hover condition, and a smaller twist would be required to obtain a constant spanwise angle of attack distribution. The result is that the advancing blade is over twisted and the tip angle of attack is too nose-down relative to the root angle of attack. In addition, since the advancing blade velocity is large, the blade root end mechanical pitch angle (due to cyclic pitch) is usually at its lowest value to reduce the advancing blade lift. This is done to balance the retreating blade lift (where the velocity is low and the pitch angle is large), so as to prevent large lateral flapping and the generation of a large steady side force. Therefore, for a typical flight condition, the net result of the nose-down cyclic pitch and the poor spanwise angle of attack distribution (due to over twist) is that the advancing blade tip angle of attack is negative, which results in negative lift in the tip region. This negative advancing blade tip airload is compounded by a high Mach number environment which can cause significant transonic effects. The result of the blade tip lift rapidly changing from a generally positive lift region over most of the rotor disk, to negative lift on the advancing side of the rotor disk, generates large vibratory airloads for a wide range of harmonics. This is similar to the large number of harmonics generated for a periodic square wave. In addition, the harmonic airloads cause blade elastic deflections which can generate additional airload harmonics, much in the same manner that collective pitch generates 1/rev and 2/rev airloads by combining with the 1/rev varia-

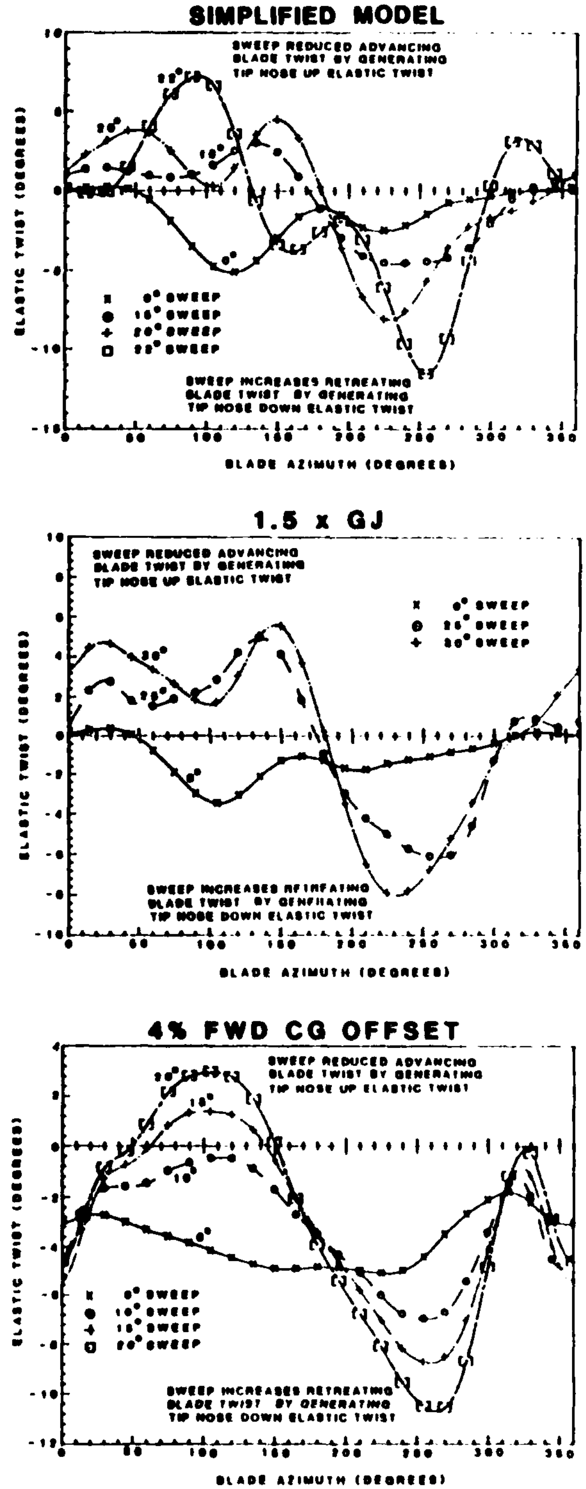

Figure 9. Elastic twist versus azimuth angle

tion of velocity around the azimuth. This large vibratory airload can cause large blade bending moments, blade flap deflections, vertical root shears and vertical hub loads. The detrimental effect of blade built-in twist on blade loads and vibratory hub loads has been substantiated by both wind tunnel test and analysis.

Based on the above discussion, it can be concluded that any process that reduces the magnitude of the rapid lift change near the tip of the advancing blade will reduce the resulting harmonic airloads and possibly the vibratory hub loads.

Figure 9 shows that for sweep configurations that reduce the 4/rev vertical hub loads, the advancing blade twist is elastically reduced and the retreating blade twist is elastically increased. This change in the blade twist is exactly what is needed to make the blade spanwise lift distribution more uniform for the advancing and retreating blade azimuth positions. In addition, the elastic untwist of the advancing blade generates a smoother rotor lift distribution versus blade azimuth, thereby reducing the vibratory airload excitation that causes vibration.

Favorable higher-harmonic elastic pitch

When the center of lift is aft of the center of elastic twist, the blade can be viewed as acting like a weather vane. A weather vane has a discrete feathering axis with the center of lift behind it and no torsional stiffness. When the wind has an angle of attack with respect to the vane, lift and drag are generated and they rotate the weather vane to a zero angle of attack. Therefore, whenever the wind direction changes and disturbs the equilibrium of the system, the vane points into the wind and returns the angle of attack to zero.

When a blade section has a positive angle of attack, lift is generated. If this lift is acting aft of the center of twist (approximately the center of gravity), a nose-down pitching moment is generated which twists the section nose down and reduces the positive angle of attack, much like the behavior of a weather vane. However, the rotor blade represents a more complicated system, since the dynamics of the rotor are involved. For a given vibratory angle of attack, the elastic pitch response (torsional elastic twist) of the blade section depends on the vibratory aerodynamic lift and pitching moment, the torsional restoring spring (including centrifugal force effects), the mass, the chordwise center of gravity, and the pitch inertia.

Depending on the dynamic properties of the blade section and the resulting dynamic elastic pitch response (amplitude and phase angle), the vibratory lift resulting from the vibratory angle of attack could be larger, the same or smaller than the angle of attack for no elastic pitch. This scenario is further complicated by the fact that a single chordwise segment of the blade is not adequate to define the total system response. The system response is dependent on the total blade twist as defined by the net of all the airloads, elastic loads and inertia loads, summed along the blade span, which in turn determines the elastic pitch response and the resulting vibratory airloads. This concept of favorable elastic twist is seen in the 4/rev tip pitch angle.

Tip pitch angle

The blade-tip pitch angle for several of the blade models used during the sensitivity study was plotted as a function of blade azimuth angle. However, like the tip angle of attack, the wave form of the blade-tip pitch angle around the azimuth for each configuration was very different for each sweep angle where the minimum hub load occurred. Hence, it appeared that the blade-tip pitch angle could not be used to help understand the hub load reduction mechanism.

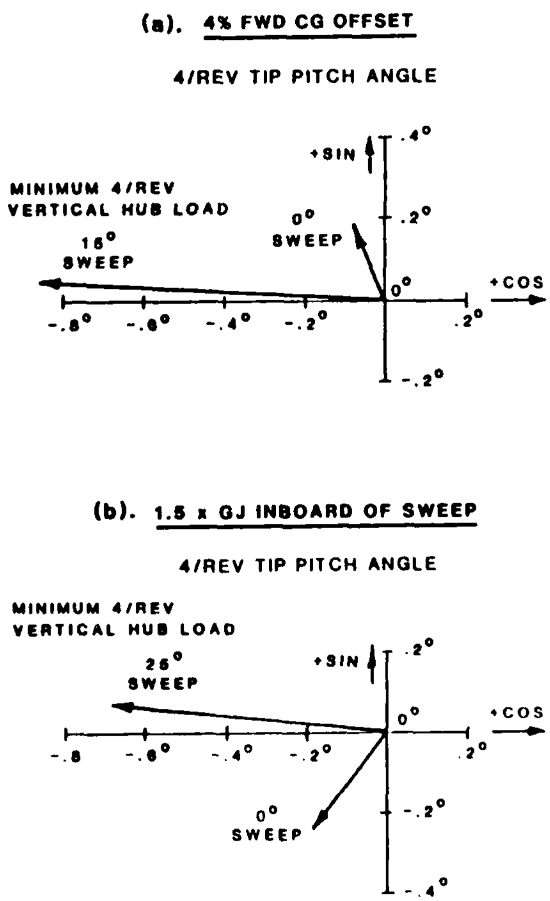

Figure 10. Effect of the sweep angle for minimum 4/rev vertical hub load on the 4/rev tip pitch angle.

However, since the 4/rev vertical hub load was reduced, it was possible that there was a significant change in the 4/rev component of the blade-tip pitch angle. Figure 10.a shows the 4/rev blade-tip pitch angle for the blade configuration with a 4%-of-chord, forward, center-of-gravity offset across the whole blade. The figure represents the 4/rev cosine and sine components. For the straight blade, the 4/rev tip pitch angle has a resultant amplitude of .204 degrees and phase angle of 110.9 degrees. For 15 degrees of aft tip sweep, which provided the minimum 4/rev vertical hub load, the tip pitch angle has a resultant amplitude of .936 degrees and a phase angle of 178.6 degrees. Figure 10.b shows the 4/rev tip pitch angle for the blade configuration with an inboard torsional stiffness factor of 1.5. The straight blade has a 4/rev tip pitch angle with a resultant amplitude of .302 degrees and a phase angle of -128.0 degrees. For 25 degrees of aft tip sweep, which provided the minimum 4/rev vertical hub load, the tip pitch angle has a resultant amplitude of .817 degrees and a phase angle of 179.3 degrees.

Is this behavior a coincidence or is the phase angle of the 4/rev tip pitch angle the mechanism for the vertical hub load reduction? At the present time, we do not know. However, there is the distinct possibility that there are forces being produced that are dependent on the tip pitch angle, and those forces are 180 degrees out of phase with other forces. *The question that needs* to be asked is, "What forces are involved in the cancellation, and what are their sources?" To explore this further would require examining the 4/rev tip pitch angle for a number of additional configurations including blade configurations where sweep did not reduce the hub loads.

Methods for checking the hypotheses

W. E. Hooper [13] demonstrated that the primary helicopter higher-harmonic airloads occur on the outboard region (.7R to the tip) of the advancing blade. This conclusion was made by examining measured H-34 rotor blade airloads over the rotor disk. When the steady, 1/rev and 2/rev airloads were removed, the resulting higher-harmonic vibratory airloads dominate the outboard region of the advancing blade. Clearly, these higher-harmonic airloads are a major source of rotor vibration for rotors with four blades or more. If this higher-harmonic air loading distribution is typical of all rotor blades, then any method that reduces these vibratory airloads or their effectiveness (by changing their spanwise distribution), could significantly reduce the vibratory blade response and the resulting vibratory hub loads.

If the above premise is valid, rotor blades with reduced vibratory hub loads should show reduced vibratory airloads. Figure 11.a shows the airload distribution for the baseline rotor (full complexity) unswept blade. The large negative lift on the tip region of the advancing blade is clearly illustrated. Figures 11.b and c also show the airload distribution for the same blade with 10 and 20 degrees of aft tip sweep, respectively. As shown, the negative lift on the tip section of the advancing blade is significantly reduced as the blade tip is swept aft. The minimum 4/rev vertical hub load is obtained for the blade with 20 degrees of aft tip sweep and clearly shows the reduced lift for the swept portion of the blade.

Figures 11.d-f show the higher-harmonic airloads (harmonics 3 through 10) for the same three blades. Table 4 shows that the straight blade has a large higher-harmonic content, a vibratory amplitude of 27.25 lbs/in with a 4/rev amplitude of 8.43 lbs/in. The blade with 10 degrees of aft tip sweep has both a smaller vibratory amplitude and a smaller 4/rev amplitude than the straight blade. The blade with 20 degrees of aft tip sweep, and the blade with almost the lowest 4/rev vertical hub loads (see Figure 2), has a larger vibratory amplitude and a smaller 4/rev amplitude than 10 degrees of sweep. Therefore, the blade with 20 degrees of aft tip sweep has the lowest 4/rev airloads and also the lowest 4/rev vertical hub load.

There are two proposed explanations, introduced earlier, for this reduction in the vibratory airloads. The first is that the aft blade sweep has caused the negative lift to elastically twist the advancing blade nose up, thereby reducing the twist on the advancing blade and reducing the *negative component* of the airload. This reduces the vibratory airloads, resulting in a reduction of

Table 4. Maximum vibratory airloading for harmonics 3-10 for the baseline rotor with nonuniform downwash.

Sweep Angle (Degrees)	Vibratory Amplitude (Lbs/In)	4/Rev Amplitude (Lbs/In)
0	27.25	8.4
10	17.93	5.5
20	23.17	5.1

Table 5. Maximum vibratory airloading for each harmonic (lbs/in) for the baseline rotor with nonuniform downwash.

Harmonic	Sweep Angle (degrees) 0	10	20
1	23.1	21.0	23.2
2	25.7	20.4	17.1
3	16.5	9.9	10.5
4	8.4	5.5	5.1
5	2.4	2.9	3.8
6	1.8	0.9	3.9
7	1.5	1.0	3.1
8	1.2	0.9	1.5
9	1.2	0.8	1.4
10	1.1	0.7	1.8

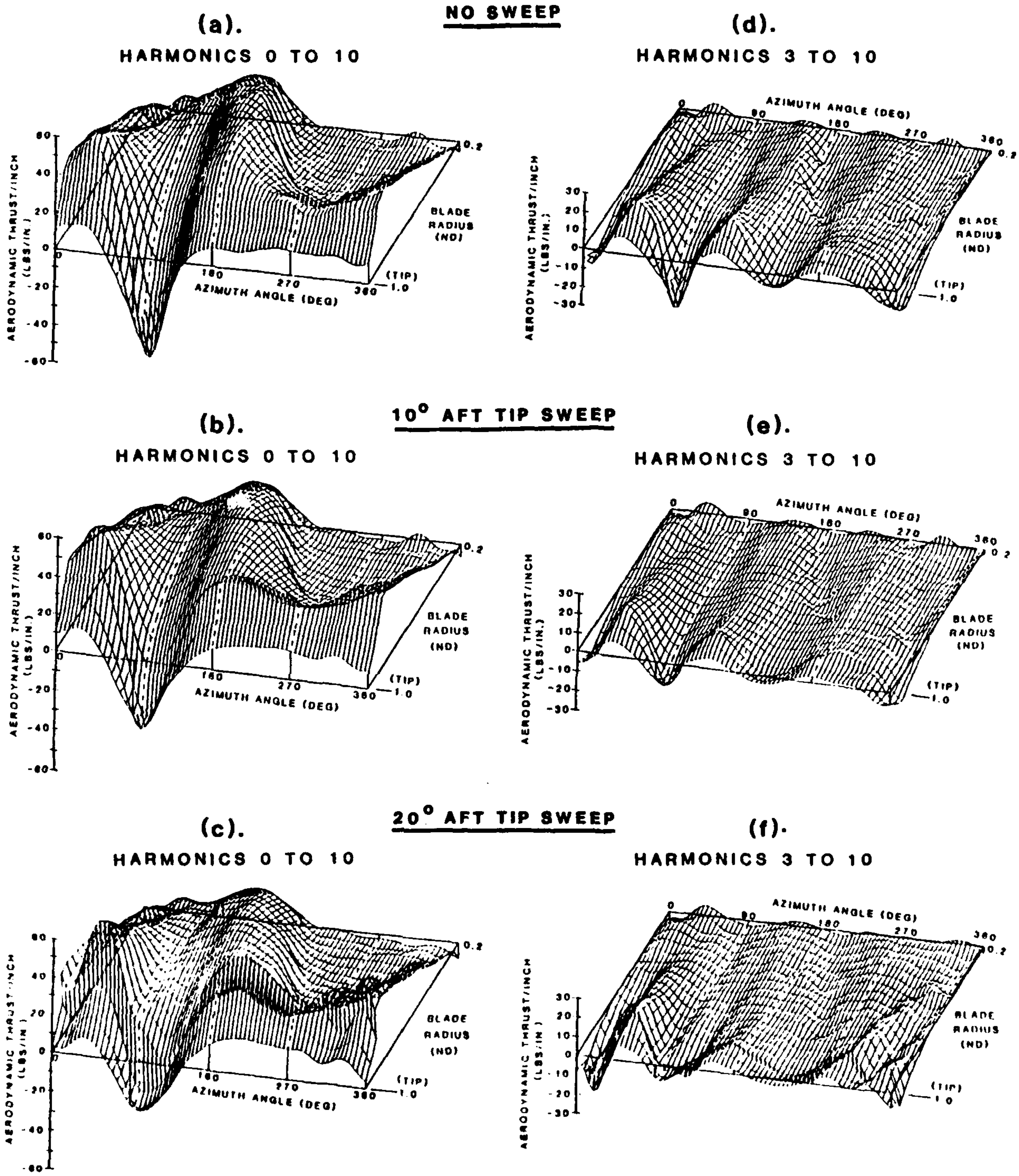

Figure 11. Total airload distribution for the baseline rotor (full complexity) with 0, 10 and 20 degrees of aft tip sweep.

all the harmonics (including the 4/rev). The second explanation is that the cg-ac coupling generates a higher-harmonic elastic twist that reduces the 4/rev airload only. If the first explanation is valid, all of the vibratory harmonics would be reduced. If the second explanation is valid, only selected harmonics of the airload (depending on the frequency and amplitude of the dynamic twist) would be reduced.

Table 5 shows the maximum airload for each harmonic for zero, 10 and 20 degrees of aft sweep. Comparing the zero and 10 degree swept blades shows a reduction in all airload harmonics, except the 5th harmonic (which increases by 21 percent). This result indicates that the hub load reduction is probably due to the first explanation, advancing blade untwist. However, the blade with 10 degrees of sweep does not have the lowest 4/rev airload or the lowest 4/rev vertical hub load (although the hub load is much lower than the unswept blade).

Comparing the 10 and 20 degree swept blades shows that all airload harmonics increase, except the 2nd and the 4th, indicating a selective harmonic airload reduction typical of the second explanation, dynamic elastic twist at specific harmonics. These conflicting conclusions suggest that the 4/rev vertical hub load reduction is a result of a combination of both mechanisms.

Conclusions

1. Substantial vibratory hub load reductions were achieved for a realistic blade using blade tip sweep. However, the original mathematical model and the blade definition were too complex to understand the source of the reduction. A simplified model was generated where the blade spanwise properties were reduced to constant values.

2. The simplified model was then used in an extensive parametric study to determine which blade properties influenced the 4/rev vertical hub loads the most. In the end, it was determined that those blade properties which were related to the dynamic torsional response of the blade were most important in determining the effectiveness of both aft and forward tip sweep. Specifically: torsional stiffness, chordwise center of gravity and mass just inboard of the sweep initiation radius were the most important parameters.

3. While the nature of the load reduction mechanism was unclear, several clues were uncovered. Our current understanding is that there is a cg-ac offset with respect to the unswept portion of the blade when the tip section is swept either forward or aft. This in turn causes a 'favorable' elastic twist which reduces the 4/rev airloads.

4. Two effects were identified which act on the blade to reduce the vibratory airloads due to tip sweep, but it was not determined if they act together or independently. These effects were advancing blade untwist, and favorable higher harmonic elastic pitch.

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